

# **Qualification Test Methods for Satellite ACS Thrusters**

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## **ABSTRACT**

Satellite attitude control system (ACS) thrusters are often required to operate at an extreme range of conditions. These include pulse mode duty cycles, propellant pressure, propellant temperature and initial thruster temperatures. The impact of test conditions on thruster operating modes can be seen in mixture ratio (MR), thrust (i.e. chamber pressure), propellant flow rates and hardware temperatures. Combining these conditions together with requirements for demonstration of performance, life (throughput), cycles and cold starts can result in a large test program with a high number of tests in order to capture all possible combinations. During the design of thruster qualification programs, the value for testing all combinations of conditions is often questioned in light of the high cost of testing. Test program scope reduction is typically achieved through the establishment of a small number of fixed conditions which are assumed to encompass the greater range of conditions. This leads to questions of the optimum selection of test condition combinations to provide a sufficient understanding of performance and thruster life while minimizing cost. The answer to each of these questions can significantly impact the cost and duration of any qualification program. The genesis of a comprehensive qualification program is discussed, including examples and experiences from past test programs and comments on existing guidelines. Recommendations for test conditions and margin selection will be made based on this accumulation of experience, past data results and a review of common mission requirements for reliability and performance.

## **INTRODUCTION**

Attitude control system (ACS) thrusters for satellites provide the forces necessary to maintain rough pointing, to provide momentum dumping, to conduct station keeping maneuvers for drift make-up and to conduct de-orbit maneuvers at the end-of-life (EOL). Depending on the exact spacecraft design and mission requirements, the operation of the thrusters and the environments they will experience can vary dramatically. In order to maintain a high degree of mission assurance, a thruster design must be qualification tested to the complete range of predicted conditions plus uncertainty and margin. Unfortunately a modern and comprehensive guide to qualification standards designed specifically for ACS thrusters is not currently available. The result can be uncertainty by program managers when developing cost, schedule and risk assessments for new thruster developments, with the follow-on result being a reluctance to develop new hardware for future programs. Uncertainty by responsible engineers may result in over or under testing, each having potentially severe program impacts. The following discussion presents basic concepts behind qualification test programs and attempts to summarize common test practices and expectations. Discussion on test margin addresses one of the most difficult and often contentious areas of qualification test design. On conclusion, an engineer or program manager should be able to utilize the information contained to begin the difficult process of qualification test program design with appropriate justifications for critical decisions. The most

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important goal of this report is for the reader to be able to develop a qualification program which ensures confidence in design capability while minimizing program cost and risk.

## QUALIFICATION OVERVIEW

Although MIL-STD-1540 was not originally designed for thruster qualification, it is one of the most widely considered documents in qualification programs and its requirements provide a valuable "intent" basis for thruster qualification design. The original versions (through Rev-C) provided comprehensive and valuable discussions (including exact values) on definition of requirements, required tests, establishment of margin, etc... Although exceptions were often taken due to its broad applicability, the information set forth provided a level of consistency between programs and suppliers. The latest revision, MIL-STD-1540D, has removed all explicit requirements in order to provide a top level discussion on test program objectives with the goal to act only as a general guide. MIL-R-5149B, "Rocket Engine, Liquid Propellant, General Specification for" provides an excellent, comprehensive guide to requirements for thrusters which can be used to define a qualification program. The document was cancelled in 1993, but remains as one of the most useful for developing performance specifications and qualification program requirements.<sup>1,2,3</sup>

MIL-STD-1540 and MIL-R-5149 provide excellent resources for designing qualification programs, however mission parameters vary widely and therefore the exact definition and configuration of tests will vary significantly depending on the mission requirements. Despite mission variations, there are several fundamental guidelines to which all qualification programs should adhere. The following test guidelines should be considered in the creation of any qualification program. More detailed discussions of each are included throughout the following sections:

1. "Test like you fly" is a common theme which can vary in the degree in which it is implemented, however the basic tenet is that test definition, configuration and order should be representative of the intended mission.
2. Every test should include explicit pass/fail criteria which are determined before the tests are conducted. Common criteria include operating temperature and performance. Every qualification program should include documentation of the test results and their relation to requirements for each test.
3. Tests should be designed to ensure perceptive measurements with which to consider pass/fail criteria. There is minimal value in a test from which the resulting data does not *perceptively* indicate the performance or health of the hardware.
4. Margins should be developed to ensure that all thrusters built within the allowable range of tolerances will be capable of meeting all mission requirements.

## QUALIFICATION TEST PROGRAM OUTLINE

The intent of a qualification test program is to demonstrate to a high level of confidence that the thruster design is capable of satisfying all mission requirements over a complete range of manufacturing variations. MIL-STD-1540D states, "The qualification test program shall assure that a design performance and safety margin exists for any mechanical, electrical or environmental stimuli that the product may reasonably expect to encounter during its service life including: (a) Assembly, integration and acceptance test at the factory, (b) Transportation, pre-mission processing and checkout at the launch site, (c) The mission, including unique characteristics of the launch vehicle, space vehicle, space environment, and age related influences." This description clearly illustrates the point that the qualification program must demonstrate, with margin, everything a thruster can reasonably expect to experience from manufacture through mission EOL.

Table 1 shows a typical top level breakdown of qualification tests, starting with manufacturing and acceptance test which are representative of the flight units. Each category shown in Table 1 should be addressed, however the method will depend on exact program requirements. For example, ground transportation and storage may drive a survival temperature range during

thermal testing, but otherwise may be satisfied by analysis. Similarly, thermal vacuum is often satisfied by a combination of thermal cycling at the valve level and vacuum hot-fire testing at the thruster level.

**Table-1**

#	Step
1	Flight Representative Manufacture
2	Flight Representative acceptance test
3	Test of Transportation and storage environments
4	Qualification level Vibe (launch)
5	Qualification level Thermal Cycle / Thermal Vacuum (may include transportation, storage and flight rqmts.)
6	Qualification Hot-fire
7	Post test NDE Inspection/verification
8	Post test Destructive evaluation

Flight representative manufacture (Step #1) and flight acceptance testing (Step #2) include the complete range of steps which are conducted during the assembly and verification of a thruster. Qualification tests should be conducted on thrusters which have undergone all of the same manufacturing processes and acceptance tests as the flight units in order to ensure the applicability of qualification results to flight hardware (*test as you fly*). An example of this is the use of chamber pressure measurement ports during qualification but not during flight. Incidents have occurred in which the volume of the port on the qualification units resulted in significantly different combustion stability behavior than the flight units without the measurement port.

Selection of the particular units for flight can be done in a number of ways. Random selection from the flight unit production line will eliminate the opportunity for assertions that a "better" unit was selected for qualification than for flight. Despite the random selection, it remains important to compare the qualification unit performance to flight unit family results in order to verify commonality. Conversely, the qualification units may be deliberately selected from a batch of flight units by comparing critical parameters (e.g. performance or temperature) and choosing units which validate the complete range (as available) of characteristics. The difficulty with this method is determining a priori which characteristics are critical with respect to qualification objectives. Whichever method is followed, it is important to *not* select units which display out of family characteristics.

Qualification level random vibration is one of the first tests done in the qualification program and is intended to qualify the launch dynamic environment of a thruster on a spacecraft. The thermal vacuum step is an excellent opportunity to verify full thruster assembly behavior at temperature extremes (including mechanical valve/injector seal performance and thermal control components), however, it is often satisfied through valve level tests and thruster hot-fire tests. Hot-fire testing is generally the longest and most expensive phase of a qualification program. The majority of the following discussion deals with the design of the hot-fire portion of a qualification program.

Following completion of a qualification test program (either successful or unsuccessful), a range of physical examinations are typically conducted. The objective of these are to determine wear patterns and the potential for incipient failure modes. Although an ideal qualification program would be 100% comprehensive of all combinations of conditions, it would also be infinitely large and expensive. Therefore a realistic program must do "sample" testing and cannot demonstrate all combinations of conditions and configurations. Therefore post test evaluation is critical to determine whether an unexpected wear-out mechanism was occurring. Examples of non-destructive evaluation (NDE) include x-ray, CAT scan (monopropellant catalyst beds), boroscope

inspection, valve performance measurements, and leak checks. Examples of destructive evaluation include general disassembly and inspection (D&I), combustion chamber coating analysis, and catalyst removal and measurement. The value of a destructive evaluation is typically traded against the lost of a qualification asset for future applications. For multi-unit qualification programs, it is recommended that at least one of the qualification thrusters undergoes post-test destructive evaluation. One example for destructive evaluation would be the determination of an incipient failure on a disilicide coated bipropellant thrust chamber. The non-linear response of coating life with propellant temperature combined with prediction uncertainty could invalidate the qualification status of a flight unit operating hotter than the qualification tests when insufficient margin is demonstrated. Finding a qualification unit incipient failure mode in such a circumstance may prompt additional testing or variations in operational modes.

## REQUIREMENTS

As in any test program, early and clear definition of requirements is critical to ensure a low cost program. Changes in any test parameter can have significant ripple effects on the whole program with the potential for extensive or even complete retesting of the thruster. In reference (4) the author describes the discovery (after the initial flight) of a steady state burn duration up to 450 seconds as compared to their qualified duration of 68 seconds. This deficiency required a requalification of the thruster to meet the correct conditions. In many instances, this type of deficiency could result in a large test program in order to achieve the conditions for qualification. For example, full duration tests should be done for the complete range of conditions and combinations (i.e. propellant temperature, inlet pressure, mixture ratio, etc...). In addition, life limiting effects such as qualification level random vibration and high propellant throughput may be necessary in order to test long duration firing results at near end of life hardware conditions. The availability of an existing qualification unit in this situation could significantly reduce the cost of re-qualifying the design for the newly discovered requirements.<sup>4</sup>

The source for qualification requirements will be a combination of documents including the mission's environmental requirements documents (ERD) which describes the complete range of environments in which the spacecraft will operate and to which components must adhere. The typical critical requirements found in the ERD or lower level supporting documentation (e.g. thermal analysis) are listed in Table 2.

**Table 2**

Temperature cycles – range and number
Dynamic environment – from launch vehicle
Shock environment – from pyrotechnic device actuation
Radiation environment – orbit dependent
Electromagnetic environment
Propellant temperature range – feed line and tank sources

A mission operations concept document (or equivalent) will describe the actual usage envisioned for the thrusters. Depending on the detail of the document, this may provide a top level understanding of the mission operating plan for the thrusters, however, it will rarely include the type of detail sufficient to develop a qualification plan (e.g. pulse duty cycle, firing duration, cold starts, hot restarts, etc...). Often the mission architect's orbit operations team must be consulted directly and repeatedly to determine these critical details.

Details such as inlet pressure and performance requirements (thrust and Isp) can typically be found in a propulsion system design document which must be generated in support of the mission concept development. Table 3 lists the operating requirements typically levied on thrusters. MIL-R-5149 provides a comprehensive list of typical requirements.

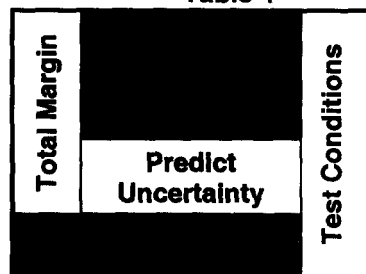
**Table 3**

Description	Requirement
Pulsed mode duty cycle	Frequency range, minimum on time, minimum off time, most common duty cycles
Burn duration (steady state or pulsed)	Maximum burn duration
Hot restarts	Number, minimum (time between firings)
Cold starts	Number
Thrust	Minimum, maximum, predictability
Specific impulse	Minimum
Propellant inlet pressure	Maximum, minimum, differential <sup>1</sup>
Impulse bit	Minimum, repeatability
Pulse centroid, t90, t10 (typically for spinning spacecraft only)	Time, repeatability

1-Differential pressure may require a combination of propellant usage rates and propellant temperature predictions

### MARGIN DISCUSSION

Some of the most difficult decisions during the design of a thruster qualification program are the establishment of margin for various test parameters. Whereas tests such as random vibration have clearly defined margins depending on the test level (i.e. duration and +db level for acceptance, proto-flight or qualification), hot-fire test margin is often a subject of controversy. A program must carefully balance the high cost of testing with the potential for unexpected future failures or anomalies due to insufficient margin. The first step in developing margin is understanding why it is needed: *Total margin accounts for (1) manufacturing variations (unit to unit), (2) the inability to test every combination of conditions and configurations, and (3) prediction uncertainty on test conditions.* This combination is shown graphically in Table 4.

**Table 4**

#### **Temperature Predict Uncertainty**

One of the more standardized aspects of margin is predict uncertainty which is applied to thermal conditions for propellant and hardware. MIL-STD-1540C calls for a minimum hot side uncertainty of 11°C for a correlated model and 17°C for uncorrelated models. The model is considered correlated once data is available either from flight or spacecraft thermal vacuum testing to verify the predictions. MIL-STD-1540C sets margin for cold side temperatures by requiring heater circuit sizing with 25% margin (i.e. predicted duty cycling at 75% or less) to account for prediction uncertainty.

Various exceptions to the hot side uncertainty margins are often considered. For example, during transfer orbit operations after launch, propellant is often assumed to be at or very near ambient (~21°C) due to the long time constant of the large propellant thermal mass. The benefit of this assumption is the ability to qualify long transfer orbit firings at a significantly reduced temperature range as compared to requirements for on-orbit operations.

A second example of exceptions to propellant temperature uncertainty is the margin applied to feed line temperatures. Typical spacecraft designs result in significantly larger temperature variations on the propellant lines than the main tanks. The result being that hot-firing tests are often characterized by a hot or cold “slug” of propellant entering the thruster first, followed by the more temperate propellant from the tanks. One method of testing this phenomenon would be to conduct the thruster test with all of the propellant at the extreme of the lines. This could result in an extreme test case with predicted temperatures as high as 50°C. In these cases, adding margin to give temperatures well over 60°C would result in unrealistic operation near a propellant boiling transition point. It is common in these cases to reduce the temperature margin in light of the hot-firing duration margin with respect to the high line temperature.

#### ***Other Margin***

Two vague areas driving margin definition are untested condition variations and manufacturing variability. The questions raised by these two concerns can easily become impossible to answer. For example:

- What is the impact of injector orifice size or surface roughness variation on atomization efficiency, temperature distribution or combustion stability?
- What is the impact of valve response times on transient ignition characteristics?
- Which combinations of oxidizer, fuel, valve, injector and combustion chamber temperatures and oxidizer and fuel inlet pressures result in the most “strenuous” conditions for thruster thermal or acoustic stability?

Whereas predict uncertainty affects propellant and hardware temperature, the variability inherent in thruster manufacturing and test can affect nearly every parameter used for tests, including: pulsed mode duty cycle, burn duration, inlet pressure and hot restart time. With the open ended nature of these questions and the lack of an authoritative resource, it falls upon the experience and discretion of the lead engineer to determine the appropriate test margins which account for all concerns. Table 5 provides recommended considerations when developing the margin for a thruster test program. For the margin recommendations, ‘predict’ is defined as the worst case flight requirement. Often the worst case occurs in a failure mode at beginning-of-life (BOL) which causes the remaining thrusters to double their lifetime usage. Failure of one thruster at BOL with no mission impact is a typical design requirement for long life (>10 years) satellites. Particular missions can have varying levels of overall system reliability requirements. Further information for these decisions can be taken from later discussions on common failure modes and areas of concern.

One unique aspect of satellite thruster qualification programs is that they rarely demonstrate margin on uncontrolled conditions despite the potential implications for life limitation. For example, the maximum allowable chamber temperature (the life limiting factor) for a disilicide coated thruster may be 2600°F, however, a program would not force the thruster to operate at 2700°F for an extended period to demonstrate this capability. Programs will often back out a temperature requirement for flight units after the qualification program by looking at the measurements taken during testing. For example, a requirement for acceptance testing at standard conditions would be based on observed qualification tests at standard conditions plus some “padding” also based on observed results during qualification (typically ~100°F). A second method for qualifying a temperature limit would be to develop a life prediction analysis and demonstrate an analytical margin on the order of 50% at the maximum allowable temperature.

**Table 5**

<b>Parameter</b>	<b>Test Margin Consideration*</b>
Inlet pressure	Max+10%, Min-10% or -10 psi (greater of)
Pressure bias (i.e. MR for bi-prop systems)	Dependant on propellant temperature variations, system pressurization factors (e.g. differential check valve delta-P), liquid side delta-P variations. Min $\pm 10$ psi
Pulse duty cycle	Margin typically not included (some programs demonstrate margin on minimum on-time pulses)
Test duration (continuous or pulse train)	Predict +50% for nominal usage at most conditions. Predict +10% for LAE backup usage
Cold starts	Predict +50%
Hot re-start	Demonstrate repeated hot restarts at times designed to maximize injector and/or valve temperature prior to ignition. Continue restarts until peak temperatures are reached.
Total number of pulses	Predict +25%
Propellant throughput (total on-time)	On-orbit predict +50% LAE backup +10%

\* "Predict" values based on worst case usage (e.g. one thruster failed at BOL).

A frequent argument encountered during qualification margin design, is that the data "appear" completely stable (i.e. temperature measurements aren't noticeably climbing) therefore the full margin duration is not necessary at all conditions. Although this would be valid in an ideal situation, extensive hot-fire test experience has shown that all of the critical temperature points are rarely measured. It is not unusual during a development to discover a condition in which all of the measurements appear to be stabilized only to experience a rapid transition in behavior driven by some unknown event. This behavior typically occurs due to one of two factors (1) a system disturbance such as a gas bubble disturbs the equilibrium with the resulting imbalance (usually thermal) causing the behavior to change dramatically; or (2) temperature at a point not directly measured becomes the driving force behind a behavior change (e.g. injector passage wall temperature causing boiling). These frequent occurrences lend support for the need to conduct full margin tests at all conditions despite perceived success at some conditions.

### **CRITICAL TEST AREAS**

A qualification hot-fire test program can be broken into two critical areas of concern, life (including stability) and performance. Each of these areas will require extensive testing in order to validate the ability to meet mission requirements and the ability to analyze on-orbit usage characteristics (i.e. propellant budget modeling). Depending on the instrumentation available, a single test at given conditions may be able to satisfy both life and performance goals. An example would be propellant flow rate in the pulsed mode. If small bellows tanks are used, then the performance test will be too short to satisfy life or stability verification. If a larger tank with a sight glass was used, then the test may be long enough to satisfy both performance and life.

Although life, stability and performance testing are commonly accepted critical areas for hot-fire testing, all areas starting from manufacture through flight should be considered for possible concerns. The goal of a comprehensive qualification is to test the environment it will experience in the order in which it will be experienced, i.e. "test like you fly." Past programs have shown that this philosophy can result in some unusual testing. Justification that other programs haven't done a particular test is not sufficient to decide that it shouldn't be done for a new program and decisions to remove particular areas of test must be backed-up by appropriate analysis. An

example of test like you fly was presented on an Astrium program. Tests for their qualification certification included, “a damp heat test, a rain test, a salt spray test, a cold vibration, a hot random vibration and a hot pyrotechnic shock test.” The described tests were performed at the module assembly level to further simulate flight configurations.<sup>5</sup>

### **Life Testing**

MIL-STD-1540C calls for demonstration of life “with suitable margin” but does not define the margin or the life limiting factors. This report assumes non-consumable thruster designs (i.e. non-ablative chamber) operated near some combustion / decomposition chamber life limiting environment. For monopropellant hydrazine thrusters this might be injection velocity and throughput; for bipropellant disilicide coated, iridium / rhenium or platinum / rhodium chambers—cold starts, throughput and chamber temperature are perceived to be life limiting. In order to develop the most effective qualification program, an advanced understanding of these life limiting factors is crucial. An example is the relationship between duty cycle and operating temperature. The ARC 5 lb<sub>f</sub> thruster (disilicide coated) has shown a characteristic in which steady state operation is always hotter than pulsed mode and has proven to be the worst case for thruster life.<sup>6</sup> In comparison, film cooled thrusters often display higher chamber temperatures in certain pulsed modes which drive the overall thermal balance to its lowest margin condition. It would be critical to demonstrate a high throughput LAE backup requirement in the worst case (i.e. hottest) pulsed mode. This example also shows the value of margin to cover the unit to unit variability since the hottest duty cycle may vary slightly from one thruster to the next.

During life testing it is important to accurately represent the true flight configuration and to look for variations in that configuration which could affect the life capability of the thruster design. The common area of concern is the heat shield design. A trade is often necessary to understand the implications of heat shield alterations for instrumentation versus the potential impact on operating temperature. Another concern, particularly with some advanced materials (e.g. iridium / rhenium) are the test cell conditions. It may be necessary to use a slow purge to prevent ambient oxygen from reacting with the exterior of the combustion chamber during testing.

Life testing should also be careful to accurately represent all flight conditions which could impact thruster life. This supports the need to “test as you fly” in order to ensure that pre-test assumptions don’t result in a missed life limiting factor. An example would be the impact of random vibration testing on a catalyst bed prior to life demonstration hot-fire testing.

Critical parameters to consider when developing life tests are: propellant throughput, pulse duty cycle, cold starts, number of pulses, propellant temperature and inlet pressure.

### **Stability Testing**

Similar to life testing, stability tests determine the capability of the thruster design to survive mission usage plans. ‘Stability’ typically describes both thermal and acoustic stability impacts on thruster life as compared to the normal wear out mechanisms. It is important to verify stability during qualification due to the potential for a rapid onset of failure in an unstable operational regime. Experience has shown that unstable operation can occur in the form of high and low frequency combustion instabilities, feed system coupling and thermal instabilities. Since deliberate destabilizing events used in launch vehicle booster engines (e.g. “bomb” tests) are difficult to implement on this small scale, validation is generally demonstrated by repeated tests of extreme combinations of conditions to full duration plus margin. Experience has shown that mixture ratio extremes at extremes of inlet pressure and temperature are the most common drivers of both thermal and combustion instability modes. While discussion of failures is rare in open literature, they are relatively common when developing new thrusters or qualifying existing designs for new conditions. One of the most difficult decisions during qualification testing is when to shutdown a firing which appears to be suffering a thermal instability. Early shutdown will protect the hardware for future tests but will often hide the true nature of the anomaly and result in a long investigation process. Late shutdown might result in a failure which can unfairly label a thruster as unreliable, but can also provide a clearer understanding of the anomalous behavior



and rapid program recovery. A failure alone should not be cause for distrust of a thruster design, lack of understanding of the cause of a failure is the true concern. It is recommended that programs follow a path of gradual extension of test duration in failure modes while evaluating data to determine root cause. While hardware should be protected if possible, a failure should not be avoided at the expense of understanding the operation.

### ***Performance Testing***

Performance of a thruster relates to all parameters which directly impact mission design or operations. For example, while the chamber temperature will have no direct impact on the mission, delivered thrust level will directly affect maneuver planning. Performance testing should be designed to generate sufficient data to (1) verify the ability of the thruster to meet mission requirements, and (2) develop models and analysis tools in support of mission operations. One of the most important and often under tested areas for developing performance prediction tools is the interactive influence coefficients for each of the various test parameters. For example, the impact of propellant temperature on specific impulse may be simple during steady state testing, but as the duty cycle changes, the impacts may change in a non-linear fashion. Further nonlinearity may result from varying duty cycles at propellant temperatures with high or low feed pressures. Still more changes may appear when mixture ratio (i.e. pressure bias) is included. The decision for the total 'resolution' of the test program (i.e. number of test points) with respect to combined conditions should be made in light of the desired accuracy of the performance modeling to be used for mission life predictions. Comprehensively mapping the complete range and combination of conditions can quickly become an overwhelming and expensive task. One recent program conducted over 900 tests on 5 thrusters through the course of the qualification program. Although that number may be high, it is important to do sufficient testing to accurately meet mission goals. As a minimum, sample testing with a variety of conditions must be done in order to accurately evaluate the accuracy of a performance model. Deliberately reducing tests in order to avoid data which show performance variations is an unacceptable method to satisfy mission requirements.

## **FAILURE MODE EXPERIENCE**

Due to competitive concerns, thruster failures are rarely discussed in open literature, however, experience has shown several areas for common thruster problems:

Combustion stability of small thrusters is often driven by accelerating propellant atomization and fuel droplet reaction rates. This can be achieved by increasing inlet pressure and propellant temperature and operating at high mixture ratios. Several instances of combustion instabilities in otherwise stable small thrusters are known to have occurred at this combination of extreme conditions. Similar conditions may inadvertently be created through the use of high vapor pressure oxidizer (i.e. high "MON" content) and gas bubbles in the propellant streams.

Gas bubbles in the propellant is one of the most dangerous and unpredictable conditions for thruster testing. Gas bubbles can initiate both thermal and combustion instabilities with erratic incidence making diagnosis extremely difficult. Often gas bubble size will also dramatically impact results. Whereas large bubbles will simply extinguish combustion and small bubbles will pass unnoticed, certain sizes in between may be sufficient to change impingement and atomization results and create a failure condition. Gas bubbles can also have the undesirable affect of accumulating in feed systems and creating a capacitance sufficient to allow coupling with the combustion chamber. Test programs will often demonstrate gas bubble ingestion in an attempt to minimize the risk and show the robustness of the design.<sup>7</sup> Such testing should attempt to vary the size of the ingested bubble and conduct tests over a variety of operating conditions.

The combination of mixture ratio (MR) with inlet pressure and temperature variations can result in test conditions which minimize the thermal margin. This is particularly concerning for fuel film cooled combustion chamber designs which often experience a non-linear response as thermal

margin is reduced and fuel film vaporizes and combusts closer to the injector face. Typically the area of greatest concern occurs at high MR and hot propellant conditions.

Hot restarts have been known to lead to unacceptable “thermal runaway” and instigation of combustion instabilities. Test programs typically verify this condition through a stair-stepping test in which ignition following the prior test is initiated at the point of peak thermal soak-back on the injector and/or valves.

Another cause of low thermal margin and potential thermal runaway is pulsed mode duty cycle. The pulsing duty cycle on both monopropellant and bipropellant thrusters has been shown to directly and often non-linearly drive thruster temperatures. Experience has shown that for monopropellant thrusters, the area of concern is often below 10% duty cycle and for bipropellant thrusters, 20% to 40% duty cycles often lead to problems.

### TEST SELECTION

An important aspect of both life and performance testing is demonstration of repeatability. In general, three to five test repeats are considered sufficient for most conditions. Additional anchor points (baseline) are often done five or more times. Extreme conditions are typically done one or two times depending on overall resolution. For example, if 20 combinations of test conditions are each tested once in a certain region, then repeating each three times is less important than if the same region was covered by only ten tests. Numerous methodologies for designing test distributions are available and are too lengthy to discuss here.<sup>8</sup> However, one common theme is to conduct sample testing with limited repeatability until anomalous results are encountered. Once anomalous results are found, the resolution and number of repeats should increase significantly.<sup>9</sup> Whatever the test selection methodology employed, the most important basic consideration is to ensure that all combinations of conditions are sample tested with sufficient test margin to ensure that no on-orbit firings are conducted outside the ‘boundaries’ demonstrated during qualification. Figure 1 shows a typical method used to display pulsed mode test points as a function of duty cycle. Figure 2 shows the typical method to display test points across inlet pressure variations.

Figure 1. Sample Pulse Mode Mapping

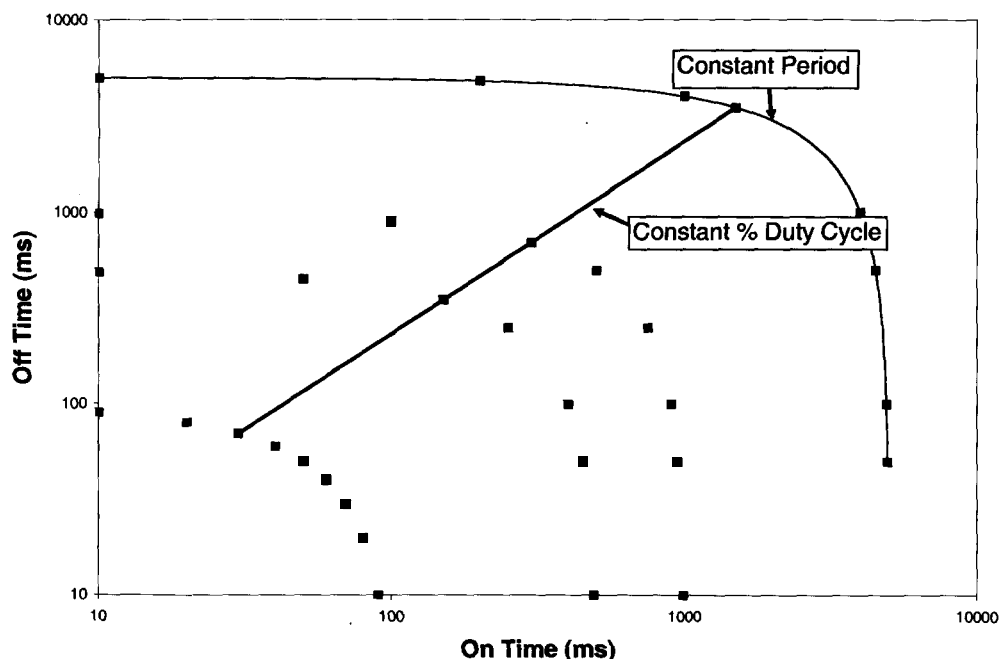
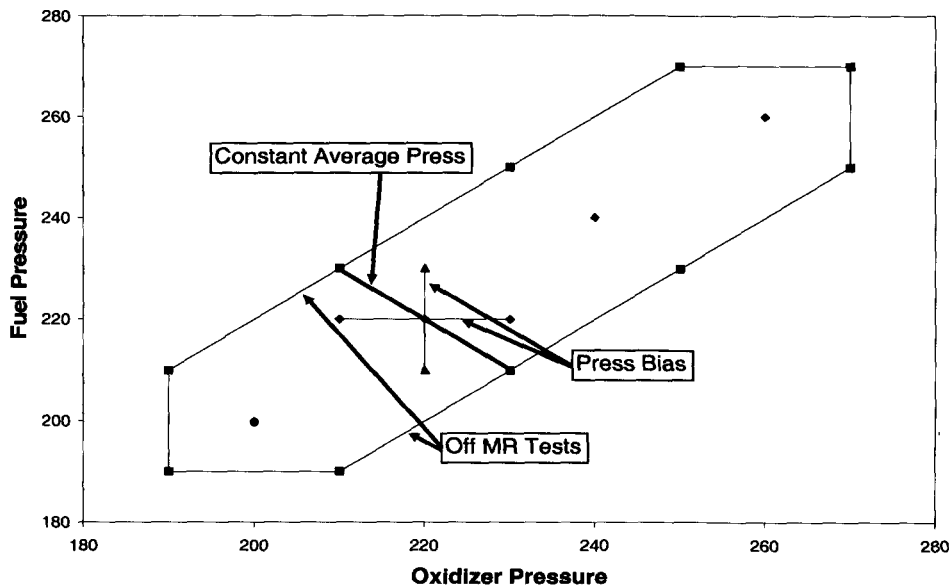


Figure 2. Pressure Range Mapping



### TEST DATA

As tests are conducted, significant quantities of data will be generated. Despite this imposing amount of data, one of the most important lessons from past programs is to carefully review all results. Programs should not rely solely on automatic redlines to determine acceptability of test results. Experience has shown numerous examples of anomalies being discovered, only to find that clear indicators of the anomalous behavior were available in qualification data which was not flagged by redlines or other standardized review processes.

Following the qualification program, it is often valuable to review results in order to determine pass fail criteria for future flight unit acceptance tests. In addition, the qualification data should act as a basis to which flight unit acceptance data are added and compared as a family database is developed. This process is invaluable for discovering problematic flight units prior to launch.

Although test instrumentation is relatively well standardized across facilities, it is important to verify the capability and accuracy of all instruments prior to testing. In addition to verifying range and calibration date, a program should ensure that the equipment used provides the desired data as directly as possible. One current example is the use of thrust measurement cells for monopropellant hydrazine thrusters. Although this has historically been conducted with pressure measurement and Cf calculations, recent programs have increasingly converted to modern techniques for highly accurate, direct thrust measurements. With modern temperature compensated strain cells and fast data acquisition systems, there is no reason for avoiding direct thrust measurement.

### TEST PROGRAM COST

Ideally a test program would be developed independent of cost considerations. In reality, the significant cost of testing will often dominate the selection criteria for hot-fire test programs. Cost implications can impact the number of tests, the length of tests, the pre-fire temperature stability, the number of thrusters tested and the types of measurements which are taken before, during

and after hot-fire tests. The simplest method to estimate test cost is determine a test rate (i.e. tests per shift) and divide it into the number of tests in the matrix, resulting in a total number of test shifts. The number of shifts is then multiplied by the per shift cost of the test cell (\$/shift) to give a subtotal cost. Other direct costs such as propellant and hardware must then be added to come up with a testing subtotal. Additional costs may be necessary to account for engineering support, data analysis, modeling generation and report writing.

One of the most sensitive factors in a cost analysis will be the test rate. A 'fast' test program on a small (~5 lb<sub>f</sub>) thruster might be able to achieve up to five tests per hour if the tests are all at nearly the same conditions with relaxed pre-fire thermal conditions specified (i.e. minimal cooling between tests). Typically two to three tests per hour are more reasonable estimates. Larger engines (e.g. 100 lb<sub>f</sub> LAE) will typically test at a much lower test rate, but also usually require significantly fewer test points. Since the test rate will be critical in determining costs, it is often desirable to expand tolerance windows on inlet pressure and pre-fire temperature. This will enable faster test rates but care must be exercised to prevent variations causing significant offsets from desired test conditions. Pre-qualification development tests can be used to determine the performance sensitivity to test condition variations which will help the engineer determine allowable tolerances which do not significantly impact results. In addition to performance variation, special care must also be given to tests intended to verify life and stability margin at the extremes. Often these points will be designated with a "-0 +X" format versus a "±X" format in order to ensure the *minimum margin* is achieved.

## CONCLUSION

Design of a qualification program which comprehensively covers all of the significant areas of concern, the critical thruster parameters and the margin necessary for high confidence flight, while minimizing cost and schedule can be a very difficult task. The preceding discussion has attempted to address some of the key points for a qualification program at a top level. A true industry standard document on this subject is highly recommended in order to standardize this complex topic and improve the ability of programs to predict the true cost of a new thruster development.

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<sup>1</sup> "Test Requirements for Launch, Upper Stage, and Space Vehicles," MIL-STD-1540C, 1994

<sup>2</sup> "Test Requirements for Launch, Upper Stage, and Space Vehicles," MIL-STD-1540D, 1994

<sup>3</sup> "Rocket Engine, Liquid Propellant, General Specification for," MIL-R-5149B, 1969.

<sup>4</sup> Holzwarth, M., Serbest, E., Rogall, H., "Qualification Test for the Ariane 5 Attitude Control System 400 N Thruster", AIAA 2003-4779, 39<sup>th</sup> AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 2003

<sup>5</sup> Schulte, G., Gotzig, U., Horsch, A., Dreer, T., "Further Improvements and Qualification Status of Astrium's 10N Bipropellant Thruster Family", AIAA2003-4776, 39<sup>th</sup> AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 2003

<sup>6</sup> Coste, K., "Qualification of the ARC 5-lbf Bipropellant Thruster For Deep Pressure Blow-Down Operation", AIAA 2001-3988, , 37<sup>th</sup> AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 2001

<sup>7</sup> Wu, P.K., Woll, P., Stechman, C., McLemore, B., Neiderman, J., Crone, C., "Qualification Testing of a 2<sup>nd</sup> Generation High Performance Apogee Thruster", AIAA#2001-3253, 37<sup>th</sup> AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 2001

<sup>8</sup> Abernethy, R. B., et al, "Weibull Analysis Handbook," USAF Wright Aeronautical Laboratories and United Technologies Corporation, AFWAL-TR-83-2079, Nov 1983.

<sup>9</sup> Krismer, D., Dorantes, A., Miller, S., Stechman, C., Lu, F., "Qualification testing of a High Performance Bipropellant Rocket Engine Using MON-3 and Hydrazine", AIAA 2003-4775, 39<sup>th</sup> AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 2003